

# Kinematical Signatures of $W^+$ Pair Production

MIROSLAV MYSKA

*Czech Technical University in Prague, FNSPE, Brehova 7, 115 19, Prague,  
Czech Republic*

The underlying event measurement may be crucial for the new physics searches at high energies at LHC. This study presents the influence of double parton scattering on the same-sign di-muon production, where only the positive charge is taken into account for now. The signal production cross section is found to be  $0.94\text{ fb}$  within the kinematic range of the ATLAS detector. This creates around 25 per cent of the total cross section for the searched final state.

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# 1 Introduction

Multiple Parton Interactions (MPI) are usually considered as a perfect tool how to describe the multi-jet production at hadron colliders, where a statistical processing plays the most important role. Measurements at SPS [1] and at Tevatron [2] provided first accurate insights into the phenomenon and studied its main signatures and cross section magnitudes. Contemporary minimum bias measurements at LHC aim for further tuning of Monte Carlo MPI models and all the subject becomes still more and more significant.

The energy of 14 TeV designed for LHC could also allow the measurements of much rare processes like vector boson pair production. In this report, pair of positively charged W bosons produced via MPI mechanism and decaying into pair of same-sign muons is studied in detail. Herwig++ program [3] is used to prepare these proton-proton signal events while the physics background processes are generated using the MadGraph's [4] matrix elements within the Herwig++ hadronization and shower tools. Single Parton Scattering (SPS) production of  $W^+W^+jj$ ,  $W^+Z$ ,  $ZZ$ , and  $t\bar{t}$  is studied in order to find the kinematical selection criteria for the best signal separation.

## 2 $W^+W^+$ Signal Generation in Herwig++

Physics motivation is to perform search for MPI effects in the new channel that has never been measured yet. The vector boson pair production is chosen as a very straightforward test of the current stage of the MPI models. The di-muon MPI signal process (see Fig. 1) consists of two hard and independent  $W^+$  creations that allow only six flavor combinations of annihilating quark-antiquark pairs:

$$u\bar{d}(75.9\%), u\bar{s}(19.4\%), u\bar{b}(3.4\%), c\bar{d}(1.3\%), c\bar{s}, c\bar{b} \rightarrow W^+ \rightarrow \mu^+\nu_\mu. \quad (1)$$

The numbers in brackets indicate the individual contributions to the matrix element for the proton-proton interaction at  $\sqrt{s} = 14$  TeV using the CTEQ6L1 PDFs [5]. The precise measurement of the cross section could bring new constraints on the geometrical coefficients  $\Theta$  [6] characterizing the prediction that different partons are distributed inside the hadron according to the different transverse distribution functions. The overlap function thus needs to carry two additional indices for interacting parton flavors and the cross section can be written as

$$\sigma_D = \frac{1}{2} \sum_{ijkl} \int \sigma_S^{ij} \sigma_S^{kl} A_k^i(b) A_l^j(b) d^2b = \frac{1}{2} \sum_{ijkl} \sigma_S^{ij} \sigma_S^{kl} \Theta_{kl}^{ij}. \quad (2)$$

The normalization of the signal process cross section is done using the widely accepted parameter called effective cross section,  $\sigma_{eff}$ . Its value of 11.5 mb used in

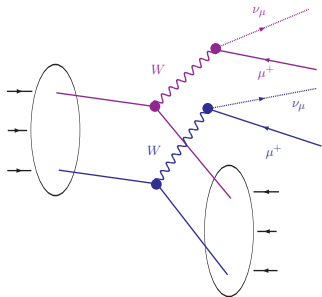


Figure 1: Schematic diagram of  $W^+$  pair production via two independent parton annihilations.

this study is derived from the CDF measurement [2] and by applying some corrections based on the considerations in [7]. The final formula for signal cross section calculation is

$$\sigma_D = \frac{\sigma_S^2}{2\sigma_{eff}}, \quad (3)$$

where  $\sigma_S$  is the usual cross section for the single  $pp \rightarrow W^+ \rightarrow \mu^+ \nu_\mu$  production.

Double Parton Scattering (DPS) term in this study denotes all the proton-proton collisions containing at least two mentioned  $W^+$  creations. This inclusive definition allows the presence of many other parton sub-processes within the same collision. Herwig++ imitates this situation very well by generating additional QCD  $2 \rightarrow 2$  parton interactions following the two main hard sub-processes. Number of these sub-processes is pre-sampled according to the Poissonian distribution calculated at the beginning of the generation. The inclusivity of the double parton process is satisfied almost perfectly because the chance of having the third  $W^+$  creation in the same collision is very small.

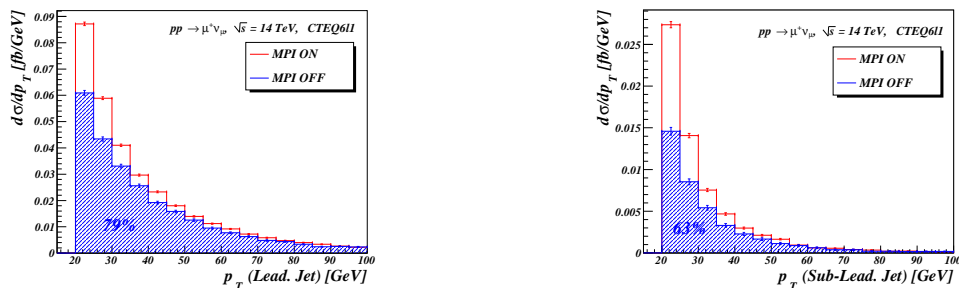


Figure 2: Transverse momentum distributions of the leading (left plot) and the sub-leading jet (right plot) using Herwig++ with MPI switched ON (red line) and OFF (blue line). The increase of the MPI fraction with decreasing jet  $p_T$  threshold is given by relatively high number of additional QCD scatterings at semi-hard level while the radiations from the primary process decrease rapidly with its  $p_T$ .

These additional QCD parton sub-interactions are also of our interest. They contribute to the underlying event and increase the amount of measured jets in the final state. For illustration, plots in Fig. 2 display the transverse momentum distributions for the hardest (leading) and for the second hardest (sub-leading) jet assuming that the event contains at least one jet (two jets in the case of the sub-leading jet distribution) with the  $p_T^{jet} > 20 \text{ GeV}$  and  $|\eta^{jet}| < 4.5$ . This threshold was set according to the

expected performance of the ATLAS detector as an example of the sensible selection [8]. The *anti* -  $k_t$  clustering algorithm [9] implemented in the FastJet package version 2.4.2 [10] was applied on the non-lepton final state particles with the radius-like parameter  $R = 0.4$ .

### 3 Selection Criteria and Background Supression

Physics background processes that could result in the final state created also by the pair of positively charged muons are studied. Background steaming from the detector-related effects (like lepton misidentification) still needs to be investigated further. Processes taken into account are Single Parton Scattering (SPS) vector boson pair production and heavy flavor quark-antiquark pair production. The former case contains all three charge combinations  $W^+W^+jj$ ,  $W^+Z$ , and  $ZZ$ , where  $Z$  denotes full matrix element for neutral boson exchange. The latter source of the same-sign

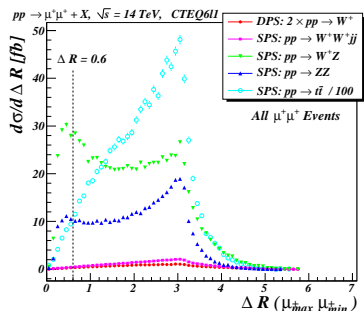


Figure 3: Differential cross section as a function of the isolation distance  $\Delta R$  in the  $\phi - \eta$  plane between two hardest positively charged muons.

muon pairs is represented here by  $t\bar{t}$  production, where the huge cross section leaves a lot of space for the muon radiation from short-living hadrons together with the heavy quark decay to hard muon.

$t\bar{t}$  events were prepared using only Herwig++. The matrix elements for the vector boson pair production were prepared using MadGraph/MadEvent generator and were reprocessed by Herwig++ in order to complete the full proton-proton collision. Parton level cuts were set as loose as possible only with one exception. Muons coming from the processes with virtual  $\gamma$  decays may propagate very close to each other, see Fig. 3. The  $W^+Z$  and  $ZZ$  productions thus had to be filtered at the parton level in order to avoid the divergences in the cross section for too

much collinear muons. The edge close to the zero is fuzzy-distributed due to the shower algorithm applied on the matrix element. The reasonable choice of the minimal relative distance between the two hardest muons in the  $\eta - \phi$  plane seems to be the value of 0.6. Further, both muons had to satisfy the minimal requirements:  $p_T(\mu^+) > 5 \text{ GeV}$ ,  $|\eta(\mu^+)| < 2.5$  that are motivated by the ATLAS detector performance [11]. The pseudorapidity cut is chosen according to the combined acceptance of the inner tracking detector and the outer muon spectrometer.

DPS events analyzed in this study are characterized only by pair of same-sign muons with tracks completely uncorrelated in any projection. The two neutrinos

from  $W$  decays do not contribute to the missing transverse energy in any significant way in comparison to SPS  $W^+Z$  production. The produced neutrino also rule out the possibility of  $W$  decay plane determination. The relative position of the two planes from separate parton sub-interactions is usually the strongest signature of the multiple parton scattering.

The selection criteria are established on the basis of kinematics of two hardest positively charged muons ( $\mu_{max}^+$  and  $\mu_{min}^+$ ) and of two hardest jets in the event. Investigated variables are, for example, transverse momentum distributions of second hardest muon and of the second hardest jet (see Fig. 4). Also muon pair and muon-jet pair characteristics (e.g. Fig. 5) are very important for the event analysis.

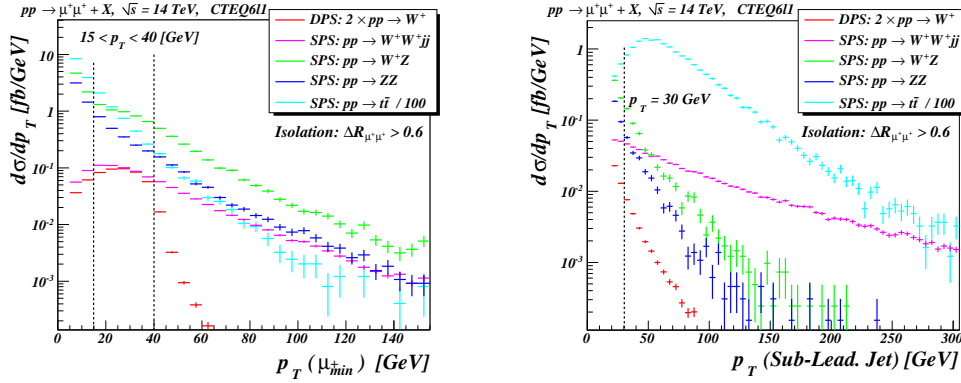


Figure 4: Differential cross section as a function of transverse momentum of the second hardest positively charged muon (left plot) and of the sub-leading jet (right plot). Distributions for  $t\bar{t}$  process were reduced by 1/100.

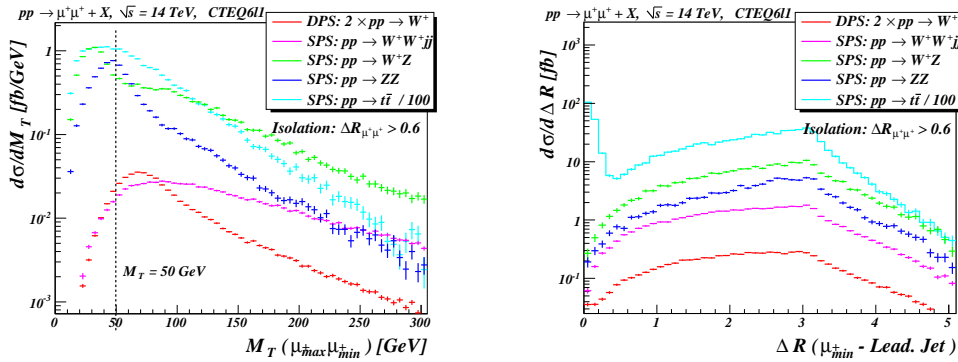


Figure 5: Differential cross section as a function of transverse mass of the positively charged muon pair (left plot) and of the distance  $\Delta R$  between the second hardest positively charged muon and the leading jet (right plot).

Especially heavy flavor quark production embodies a strong jet background which can be used for the signal selection. Nevertheless, there is still a non-negligible signal event fraction also with hard jets coming from QCD MPI or initial state radiations. Simple isolation criteria between jets and muons can filter off a large amount of  $t\bar{t}$  processes.

The final selection criteria strongly depends on the transverse momentum threshold of efficient muon detection and on the hadron calorimeter acceptance. The lower  $p_T$  limit of the muon detection is considered, the more background can be filtered off. Similarly, the larger calorimeter acceptance and the larger cone-like parameter  $R$  for the clustering algorithm is used, the more jets can be kept in the event for further analysis. A very sensitive approach is necessary because of the low signal cross section. The contemporary stage of the study leads to the following *Final selection* criteria:

$$\begin{array}{llll}
20 \text{ GeV} < p_T(\mu_{max}^+) < 50 \text{ GeV} & 15 \text{ GeV} < p_T(\mu_{min}^+) < 40 \text{ GeV} \\
M(\mu_{max}^+ \mu_{min}^+) > 20 \text{ GeV} & M_T(\mu_{max}^+ \mu_{min}^+) > 50 \text{ GeV} \\
p_T(\mu_{max}^-) < 5 \text{ GeV} & missing E_T > 20 \text{ GeV} \\
p_T(jet_{lead.}) < 40 \text{ GeV} & p_T(jet_{s-lead.}) < 30 \text{ GeV} \\
\Delta R_{\mu^+ jet} > 0.4 & \Delta R_{\mu_{max}^+ \mu_{min}^+} > 0.6
\end{array}$$

All the cross sections for individual contributions to the searched di-muon final state are written in Table 1. *All Events* category contains all events where muons have to satisfy

$$p_T(\mu^+) > 5 \text{ GeV}, \quad |\eta(\mu^+)| < 2.5, \quad \Delta R(\mu_{max}^+ \mu_{min}^+) > 0.6. \quad (4)$$

Double parton scattering here is completely overwhelmed by background. Two main selections follow. First, the *Negative muon veto* rejected events containing a negatively charged muon with  $p_T(\mu^+) > 5 \text{ GeV}$ . Almost one third of the remaining  $W^+Z$  and  $ZZ$  background can be further separated by going down to  $3 \text{ GeV}$   $p_T$  cut without observable change of signal contribution. Unfortunately, trigger efficiencies and other detector effects have not been studied yet. Second substantial selection is the *Jet veto*. Here, events containing at least one jet with  $p_T > 20 \text{ GeV}$  are rejected. This selection filters significantly the  $W^+W^+jj$  and  $t\bar{t}$  contributions off but keeps only 60% of the signal events. Therefore the *Final selection* releases this jet cut a little bit and uses the isolation cut. Additionally, the b-tagging is supposed to reduce the  $t\bar{t}$  background at least by 50% but it is not involved here. Total cross section for the searched di-muon final state is predicted to be around  $3.66 \text{ fb}$  while the signal-to-background ratio is 0.35. Necessary integrated luminosity recorded e.g. by the ATLAS detector has to be above  $103 \text{ fb}^{-1}$  to reach the signal significance at least five standard deviations above the background.

$\sigma$ [fb]	DPS Signal	SPS Background			
	$W^+W^+$	$W^+W^+jj$	$W^+Z$	$ZZ$	$t\bar{t}$
<i>All events</i>	1.96	4.59	68.21	36.41	$8.8 \times 10^3$
<i>Negative muon veto</i>	1.95	4.54	19.81	2.87	$6.7 \times 10^3$
survived	99%	99%	29%	8%	76%
<i>Jet veto</i>	1.18	0.14	46.48	25.74	13.66
survived	60%	3%	68%	71%	<1%
<i>Final selection</i>	0.94	0.06	1.93	0.13	0.59
survived	48%	1%	3%	<1%	<<1%

Table 1: Summary of five studied processes characterized by production cross sections in femto-barns as well as by the fractions of appropriate events surviving the individual selections.

## 4 Summary and Conclusions

The importance of the double parton scattering was outlined in the manner of the increasing energy and luminosity available at the LHC. Relatively new Herwig++ generator incorporates the eikonal model of hadron interactions and provides very useful tool for the estimation of the particle behavior within the multiple parton scattering. This study uses its model in order to generate proton-proton collisions at  $\sqrt{s} = 14$  TeV, where pair of positively charged gauge bosons is produced via two independent quark-antiquark annihilations occurring within the same collision. The muon decay channel is studied in detail. The studied background processes include the single parton scattering producing gauge boson pair with any charge combination or heavy flavor quark pair. The latter is represented here by the analysis of  $t\bar{t}$  events. The background processes were prepared using both MadGraph and Herwig++ programs in order to study complete events including showering and hadronization procedures.

Several mechanisms were studied in order to find the kinematical region for the statistically reasonable measurement of the double parton scattering. Roughly speaking, the strict event veto on the negatively charged muons filters most of the single parton processes producing at least one neutral gauge boson. Process  $pp \rightarrow W^+W^+jj$  and heavy flavor quark production are suppressed mostly by selecting events without any hard jet (with  $p_T > 40$  GeV). The *Final selection* predicts the double parton scattering cross section to be approximately 0.9 fb. Signal-to-background ratio reaches 0.35. The true result will strongly depend on the detector performance and on the trigger efficiencies that are not incorporated in this study. The integrated luminosity is required to be very large, of  $\mathcal{O}(100\text{fb}^{-1})$ . However, the LHC could provide enough of statistics within a few years of full energy operation.

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